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DESCRIPTION

RANKINE CYCLE SYSTEM

FIELD OF THE INVENTION

The present invention relates to a Rankine cycle system that includes an evaporator for heating a liquid-phase working medium with exhaust gas of an engine so as to generate a gas-phase working medium, and a displacement type expander for converting the thermal energy of the gas-phase working medium generated in the evaporator into mechanical energy.

BACKGROUND ART

Japanese Utility Model Registration Publication No. 2-38161 discloses an arrangement in which the steam temperature at the outlet of a waste heat once-through boiler using, as a heat source, exhaust gas of an engine rotating at a constant speed is compared with a target steam temperature, and the amount of water supplied to the waste heat once-through boiler is feedback-controlled so as to make the steam temperature coincide with the target steam temperature, precision in control of the steam temperature being improved by adding, to the feedback signal, a feedforward signal calculated on the basis of the steam pressure at the outlet of the waste heat once-through boiler so as to compensate for fluctuations in the engine load.

As shown in FIG. 12, in a Rankine cycle system, in order for the output of an expander to be positive, that is, in order to extract mechanical energy from the expander, it is necessary to control the steam temperature at the outlet of an evaporator so that it is at least the saturated steam temperature. Furthermore, as shown in FIG. 13, the efficiency of the evaporator and the efficiency of the expander change according to the steam temperature, and in order to maximize the total efficiency of the two, it is necessary to control the

steam temperature at an optimum temperature. However, as shown in FIG. 4A, when the amount of water supplied to the evaporator is changed stepwise, since the responsiveness with which the steam temperature changes is poor, it takes a few tens of seconds to a few hundred seconds to reach a steady state, and it is therefore difficult to control the steam temperature at the outlet of the evaporator with good responsiveness and high precision by changing the amount of water supplied to the evaporator in a vehicular Rankine cycle system in which there are rapid fluctuations in the engine load.

In order to control the steam temperature with good responsiveness by changing the amount of water supplied, it is necessary to reduce the heat capacity of the evaporator, and it is accordingly necessary for the evaporator to have a small casing and a short heat transfer pipe length, but this gives rise to the problems that the evaporator cannot generate a sufficient amount of steam or the efficiency of the evaporator is degraded.

DISCLOSURE OF THE INVENTION

The present invention has been achieved under the above-mentioned circumstances, and it is an object thereof to control the temperature of a gas-phase working medium generated in an evaporator of a Rankine cycle system at a target temperature with good responsiveness and high precision.

In order to attain this object, in accordance with the present invention, there is proposed a Rankine cycle system that includes an evaporator for heating a liquid-phase working medium with exhaust gas of an engine so as to generate a gas-phase working medium, and a displacement type expander for converting the thermal energy of the gas-phase working medium generated in the evaporator into mechanical energy, characterized in that the system includes control means for controlling the amount of liquid-phase working medium supplied to the evaporator and the rotational speed of the expander

so as to make the temperature of the gas-phase working medium at the outlet of the evaporator coincide with a target temperature.

In accordance with this arrangement, by controlling the amount of liquid-phase working medium supplied to the evaporator, which heats the liquid-phase working medium with the exhaust gas of the engine and generates the gas-phase working medium, and controlling the rotational speed of the displacement type expander, which converts the thermal energy of the gas-phase working medium generated in the evaporator into mechanical energy, it is possible to make the temperature of the gas-phase working medium generated in the evaporator coincide with the target temperature with good responsiveness and high precision, thereby maximizing the total efficiency, which is the sum of the efficiency of the evaporator and the efficiency of the expander.

A controller 20 of embodiments corresponds to the control means of the present invention.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 to FIG. 9 show a first embodiment of the present invention; FIG. 1 is a diagram showing the overall arrangement of a Rankine cycle system, FIG. 2A to FIG. 2D are diagrams showing the temperature distribution of a working medium within an evaporator, FIG. 3 is a graph showing changes in the steam pressure and the steam temperature when the rotational speed of an expander is changed stepwise, FIG. 4A to FIG. 4C are graphs showing changes in the steam temperature when the amount of water supplied and the rotational speed of the expander are changed simultaneously, FIG. 5 is a flowchart of a steam temperature control main routine, FIG. 6 is a flowchart of a water supply amount feedforward value calculation routine, FIG. 7 is a flowchart of an expander target rotational speed calculation routine, FIG. 8 is a

map for looking up a fuel flow rate G_F from engine running conditions such as an engine rotational speed Ne and an intake negative pressure Pb, and FIG. 9 is a map for looking up a water supply amount feedforward value Q_{FF} from an exhaust gas flow rate G_{GAS} and an exhaust gas temperature Tg. FIG. 10 and FIG. 11 show a second embodiment of the present invention; FIG. 10 is a flowchart of a steam temperature control main routine related to the second embodiment, and FIG. 11 is a map for looking up an amount of rotational speed change ΔN_{EXP} from a steam flow rate and a deviation T_0 - T. FIG. 12 is a graph showing the relationship between steam temperature and expander output, and FIG. 13 is a graph showing the relationship between the optimum steam temperature and the maximum efficiency of an evaporator and the expander.

BEST MODE FOR CARRYING OUT THE INVENTION

Modes for carrying out the present invention are now explained with reference to embodiments of the present invention shown in the attached drawings.

As shown in FIG. 1, a Rankine cycle system for recovering the thermal energy of exhaust gas of a vehicle engine 11 is formed from an evaporator 12 for heating a liquid-phase working medium (water) with the exhaust gas of the engine 11 and generating a high temperature, high pressure gas-phase working medium (steam), a displacement type expander 13 for converting the thermal energy of the high temperature, high pressure steam generated in the evaporator 12 into mechanical energy, a condenser 14 for cooling the steam discharged from the expander 13 and condensing it into water, a tank 15 for storing water discharged from the condenser 14, a water supply pump 16 for drawing up water out of the tank 15, and an injector 17 for injecting water

drawn up by the water supply pump 16 into the evaporator 12, the above being arranged in a closed circuit.

A motor/generator 18 connected to the expander 13 is disposed, for example, between the engine 11 and driven wheels; the motor/generator 18 can be made to function as a motor so as to assist the output of the engine 11, and when the vehicle is being decelerated the motor/generator 18 can be made to function as a generator so as to recover the kinetic energy of the vehicle as electrical energy. The motor/generator 18 may be connected to the expander 13 alone, and then exhibits only the function of generating electrical energy. In the present invention, the rotational speed of the expander 13 is controlled by regulating the load (amount of electric power generated) of the motor/generator 18 so as to regulate the load imposed on the expander 13 by the motor/generator 18. A controller 20, into which are input running conditions of the engine 11, that is, an engine rotational speed Ne, an intake negative pressure Pb, an exhaust gas temperature Tg, and an air fuel ratio A/F, together with a steam temperature T at the outlet of the evaporator 12 detected by a steam temperature sensor 19, controls the amount of water supplied from the injector 17 (or the rotational speed of the water supply pump 16) and the load generated by the motor/generator 18, that is, the rotational speed of the expander 13.

The reason why the steam temperature at the outlet of the evaporator 12 can be controlled by regulating the rotational speed of the expander 13 is now explained.

FIG. 2A shows schematically the structure of the evaporator 12. A heat transfer pipe 22 disposed within a casing 21 of the evaporator 12 includes a water inlet 22a communicating with the injector 17, and a steam outlet 22b communicating with the expander 13, and the casing 21 includes an exhaust

gas inlet 21a on the steam outlet 22b side and an exhaust gas outlet 21b on the water inlet 22a side. The working medium and the exhaust gas therefore flow in opposite directions to each other.

As shown in FIG. 2B, the temperature of water supplied to the water inlet 22a of the heat transfer pipe 22 increases gradually in a liquid phase state, and when it reaches a saturation temperature at point a, it becomes wet saturated steam (two phase state) in which water and steam coexist and the saturation temperature is maintained. When all the water becomes superheated steam in a gas phase state at point b, the temperature of this steam increases from the saturation temperature. As shown in FIG. 3, if the load of the motor/generator 18 is reduced and the rotational speed of the expander 13 is increased stepwise while keeping the amount of steam supplied to the expander 13 constant, the steam pressure decreases, and the steam temperature decreases temporarily due to the latent heat of evaporation of water and the heat of expansion of water. That is, as shown in FIG. 2C, the saturation temperature decreases and point a and point b shift to the water inlet 22a side, and the temperature of steam discharged from the steam outlet 22b decreases temporarily. The speed of decrease in the steam temperature is proportional to the speed of decrease in the steam pressure and is on the order of a few seconds. Subsequently, as shown in FIG. 2D, the working medium within the heat transfer pipe 22 receives the thermal energy of exhaust gas, its temperature increases and, as shown in FIG. 3, its temperature returns to the temperature before the rotational speed of the expander 13 was increased. Since this temperature change is influenced by the heat capacity of the evaporator 12, it is on the order of a few tens of seconds to a few hundred seconds. In this way, by changing the rotational speed of the expander 13, it is possible to control the steam temperature at

the outlet of the evaporator 12 with good responsiveness, although this is temporary.

As described above, since the change in steam temperature due to the change in rotational speed of the expander 13 is temporary, and the steam temperature returns to its original temperature as time elapses, the amount of water supplied from the injector 17 to the evaporator 12 is controlled at the same time as the rotational speed of the expander 13 is changed. When, for example, in order to increase the steam temperature at the outlet of the evaporator 12, the amount of water supplied to the evaporator 12 is decreased stepwise as shown in FIG. 4A, the steam temperature at the outlet of the evaporator 12 increases slowly, taking on the order of a few tens of seconds to a few hundred seconds, and converges to a predetermined temperature. In this way, controlling the steam temperature by changing the amount of water supplied has very poor responsiveness, but by simultaneously temporarily increasing the steam temperature as shown in FIG. 4B by decreasing the rotational speed of the expander 13 stepwise it is possible, as shown in FIG. 4C, to control the steam temperature at a target steam temperature with good responsiveness and high precision, and as a result it is possible to maximize the total efficiency, which is the sum of the efficiency of the evaporator and the efficiency of the expander.

The above-mentioned operation is now explained further with reference to flowcharts of FIG. 5 to FIG. 7.

Firstly, in step S1 the steam temperature T at the outlet of the evaporator 12 is detected by the steam temperature sensor 19, in step S2 the running conditions of the engine 11, that is, the engine rotational speed Ne, the intake negative pressure Pb, the exhaust gas temperature Tg, and the air

fuel ratio A/F are detected, and in step S3 a water supply amount feedforward value Q_{FF} is calculated on the basis of Ne, Pb, Tg, and A/F.

FIG. 6 shows a sub routine of step S3 above; in step S11 a fuel flow rate G_F of the engine 11 is looked up by applying the engine rotational speed Ne and the intake negative pressure Pb to the map of FIG. 8. The greater the engine rotational speed Ne and the higher the intake negative pressure Pb, the greater the fuel flow rate G_F. The reason why the fuel flow rate G_F rapidly increases in a region where the intake negative pressure Pb is high is because the fuel becomes rich when the load of the engine 11 is high. In the subsequent step S12 the exhaust gas flow rate G_{GAS} is calculated from the air fuel ratio A/F and the fuel flow rate G_F by means of $(A/F + 1) \times G_F$. In step S13 the water supply amount feedforward value Q_{FF} is looked up by applying the exhaust gas flow rate G_{GAS} and the exhaust gas temperature Tg to the map of FIG. 9. The greater the exhaust gas flow rate G_{GAS} and the higher the exhaust gas temperature Tg, the greater the water supply amount feedforward value Q_{FF}. The water supply amount feedforward value Q_{FF} is corrected so as to increase slightly in response to an increase in the target steam temperature T_0.

When the water supply amount feedforward value Q_{FF} is calculated in this way, the procedure returns to the flowchart of FIG. 5, and in step S4 a water supply command value for the injector 17, that is, a degree-of-opening command value Ti for the injector 17, is calculated from the water supply amount feedforward value Q_{FF}. Since the amount of water supplied changes in response to the rotational speed of the water supply pump 16, instead of step S4 above, in step S4' a water supply command value for the injector 17, that is, a rotational speed Np of the water supply pump 16, may be calculated from the water supply amount feedforward value Q_{FF}.

In the subsequent step S5 a target rotational speed N_{EXP} for the expander 13 in order to control the steam temperature T at a target steam temperature T_0 is calculated. FIG. 7 shows a sub routine of step S5 above; if in step S21 the steam temperature T exceeds the target steam temperature T_0, then in step S22 an amount of rotational speed change ΔN_{EXP} is added to the target expander rotational speed N_{EXP}, whereas if the steam temperature T is equal to or less than the target steam temperature T_0, then in step S23 the amount of rotational speed change ΔN_{EXP} is subtracted from the target expander rotational speed N_{EXP}. In step S6 of the flowchart of FIG. 5, the target expander rotational speed N_{EXP} is output as a command value, and the load generated by the motor/generator 18 is changed so as to control the rotational speed of the expander 13.

A second embodiment of the present invention is now explained with reference to FIG. 10 and FIG. 11. The flowchart of FIG. 10 is one in which steps S3A and S3B are added after step S3 (calculation of water supply amount feedforward value) of the flowchart (first embodiment) of FIG. 5, and the other steps are substantially the same. That is, in step S3A a water supply amount feedback value Q_{FB} is obtained as a PID calculation value of a deviation T_0 - T of the steam temperature T from the target steam temperature T_0. In step S3B a water supply amount Q_0 is calculated by adding the water supply amount feedback value Q_{FB} to a water supply amount feedforward value Q_{FF}, and in step S4 (or step S4') a water supply amount command value is calculated on the basis of the water supply amount Q_0.

When a target expander rotational speed N_{EXP} is calculated in step S5 (see FIG. 7), as shown in FIG. 11, when the steam flow rate is low, even if an amount of rotational speed change ΔN_{EXP} for the target expander rotational speed N_{EXP} is small, the steam temperature can be changed, but when the

steam flow rate is high, unless the amount of rotational speed change ΔN_{EXP} for the target expander rotational speed N_{EXP} is made large, the steam temperature cannot be changed. The expander rotational speed can be rapidly converged to the target expander rotational speed N_{EXP} by increasing the amount of rotational speed change ΔN_{EXP} when the deviation T_0 - T of the steam temperature T from the target steam temperature T_0 is large and by decreasing the amount of rotational speed change ΔN_{EXP} when the deviation T_0 - T is small.

As hereinbefore described, in accordance with the second embodiment, the combined use of feedforward control and feedback control enables the expander rotational speed to be converged to the target expander rotational speed N_{EXP} yet more precisely.

Although embodiments of the present invention are explained in detail above, the present invention can be modified in a variety of ways without departing from the spirit and scope thereof.

For example, in the flowchart of FIG. 6 the water supply amount feedforward value Q_{FF} is calculated on the basis of Ne, Pb, Tg, and A/F, but it may be obtained by directly detecting an exhaust gas flow rate using a flow rate sensor.

Furthermore, in step S11 of the flowchart of FIG. 6 the fuel flow rate G_F of the engine 11 is looked up from the map using the engine rotational speed Ne and the intake negative pressure Pb, but it may be calculated from a fuel injection quantity of the engine 11.

Moreover, the working medium is not limited to water (steam), and another appropriate working medium may be employed.